High energy density physics experiments with intense heavy ion beams

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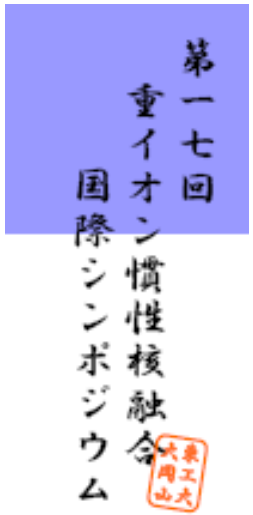


17th International Symposium on Heavy Ion Inertial Fusion,
Tokyo, Japan *August 3-8, 2008*

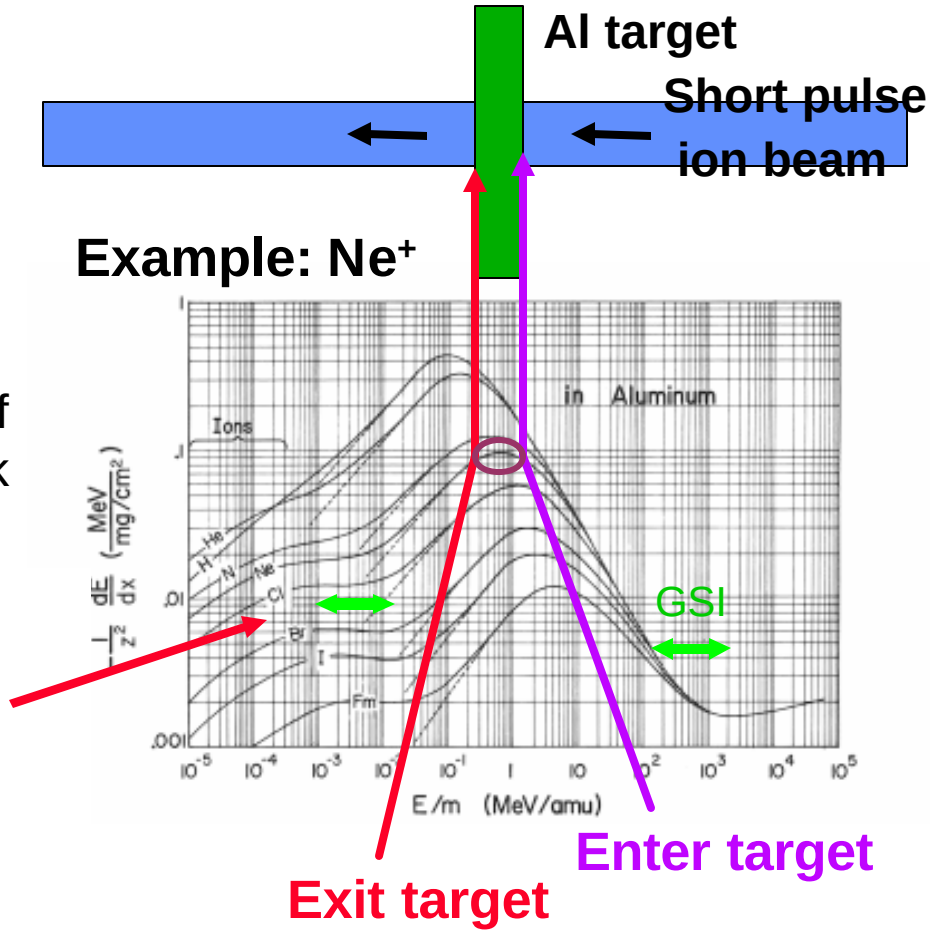
This work performed under the auspices of the U.S Department of Energy by University of California, Lawrence Livermore and Lawrence Berkeley National Laboratories under contracts No. W-7405-Eng-48 and DE-AC02-05CH11231.

Outline of talk

- Ion-driven warm dense matter
- Warm Dense Matter (WDM) target chamber, targets, and diagnostics
- Experimental plan and target simulations

Ion beams provide a tool for generating homogeneous warm dense matter.

- Warm dense matter (WDM)
  - T ~ 0.1 to 10 eV
  - ρ ~ 0.01 -1 * solid density
- WDM strategy: maximize uniformity and the efficient use of beam energy by placing Bragg peak at center of foil (NDCX-2)
- Alternate: uniform pedestal for heavy ions at lower beam energy (~NDCX-1)



Northcliffe, Schilling

Characteristics of ion beam driven HEDP/WDM.

Precise control of energy deposition

Sample size large compared to diagnostic resolution volumes (~ 1 micron thick by ~ 1 mm diameter)

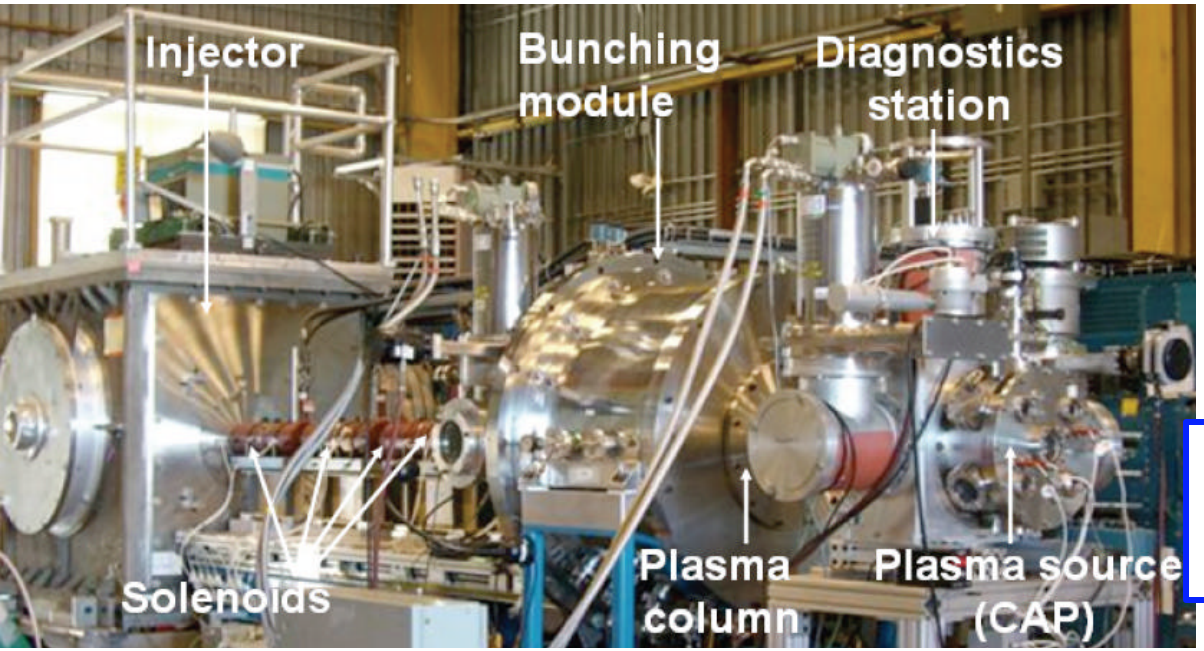
Uniform energy deposition (<~ 5%)

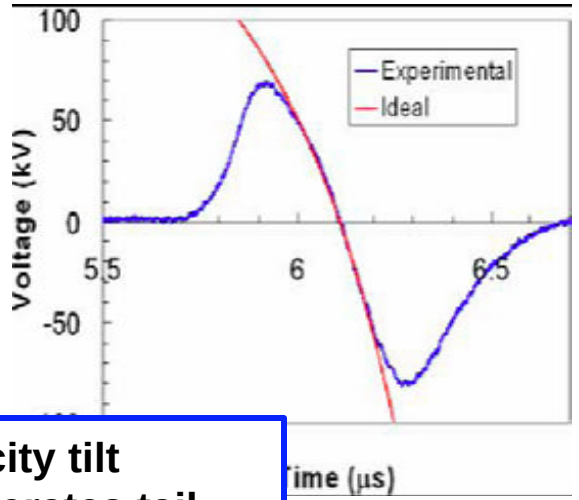
Able to heat any target material (conductors, insulators, foams, powders, ...)

A benign environment for diagnostics

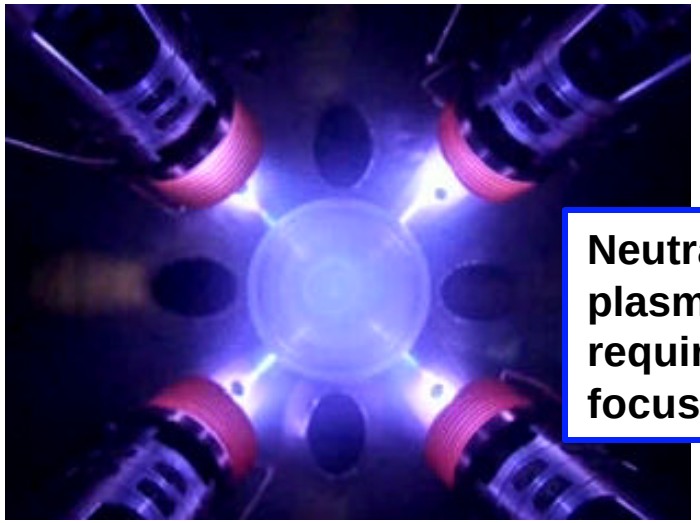
High repetition rates (10/hour to 1/second)

NDCX-I has demonstrated simultaneous transverse focusing and longitudinal compression of K^+ beam.

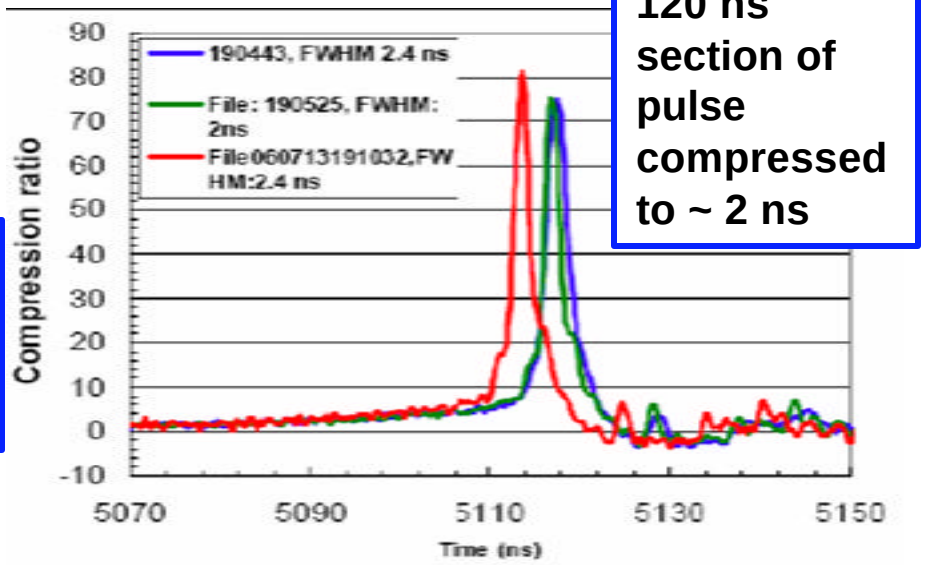




Velocity tilt accelerates tail, decelerates head

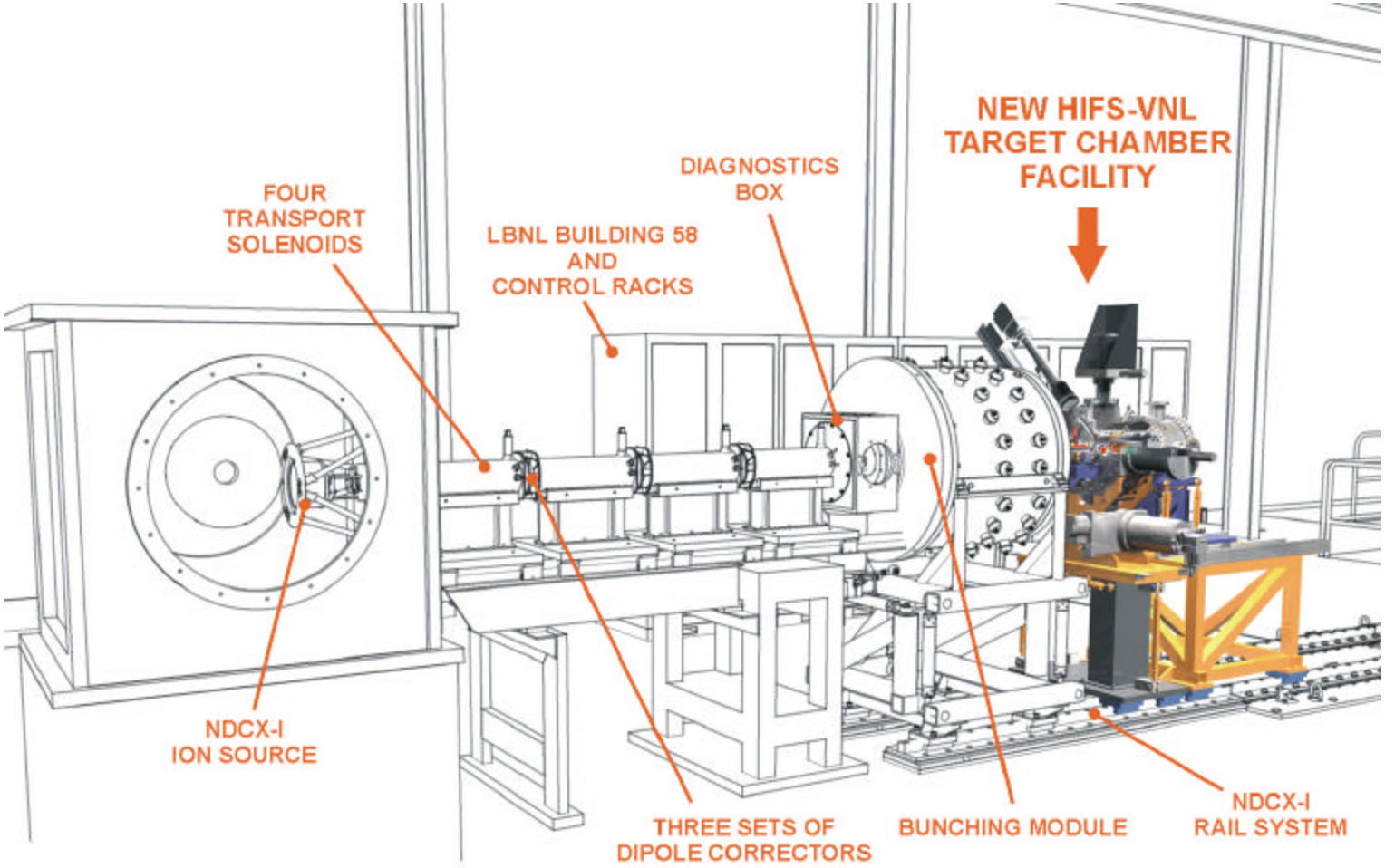


Neutralizing plasma is required for final focus



120 ns section of pulse compressed to ~ 2 ns

New WDM target chamber is installed on NDCX-I.



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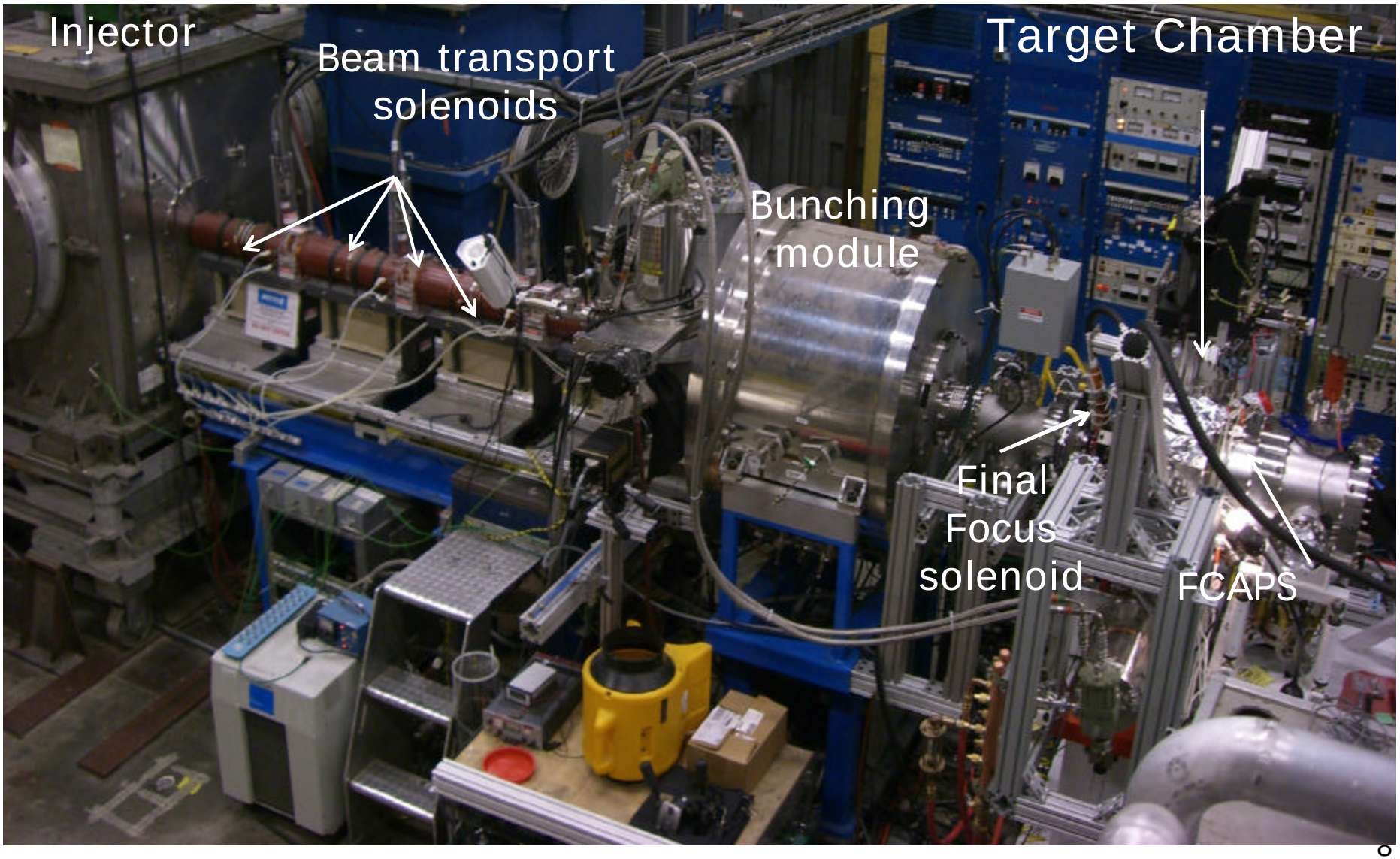
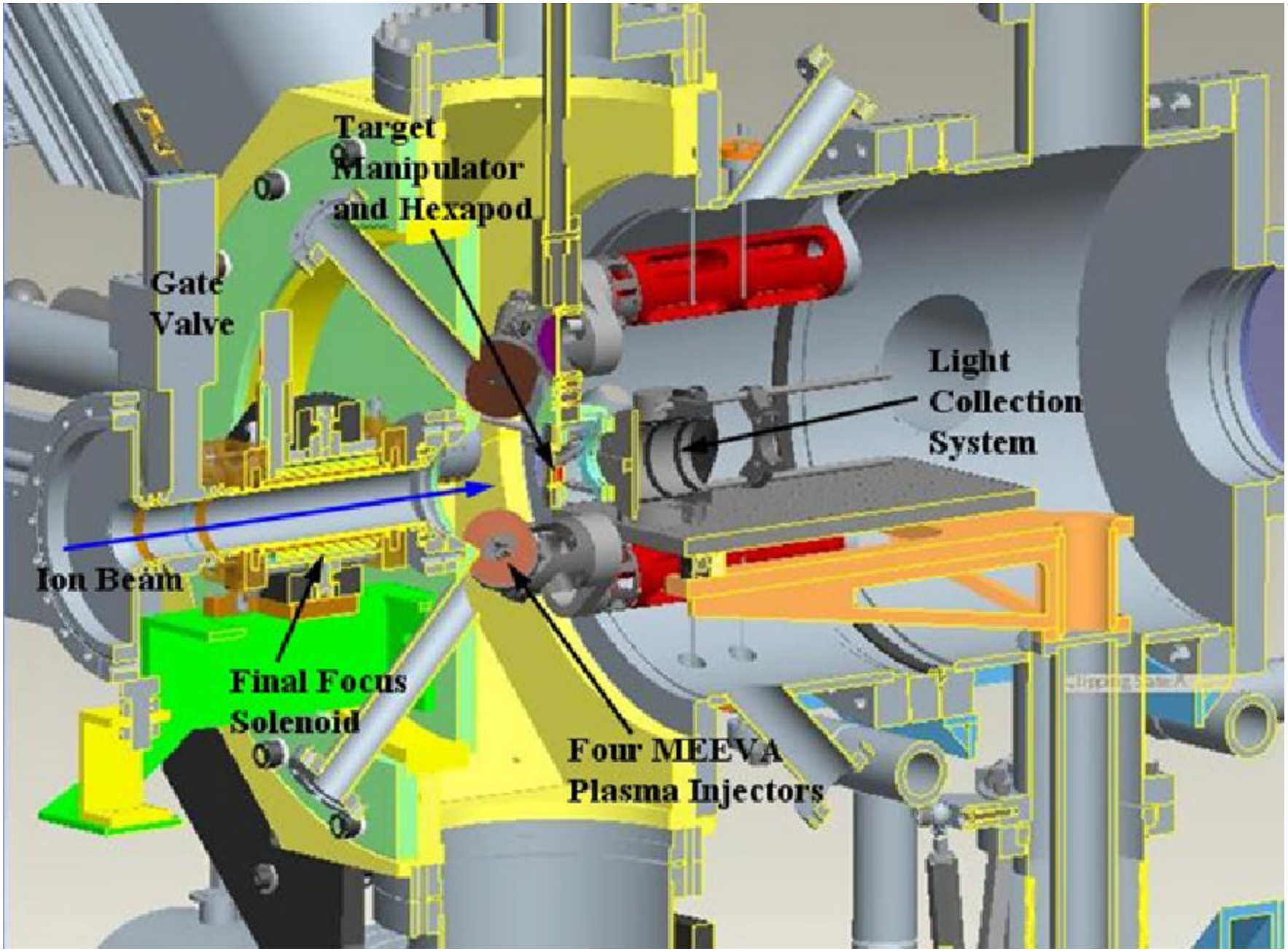
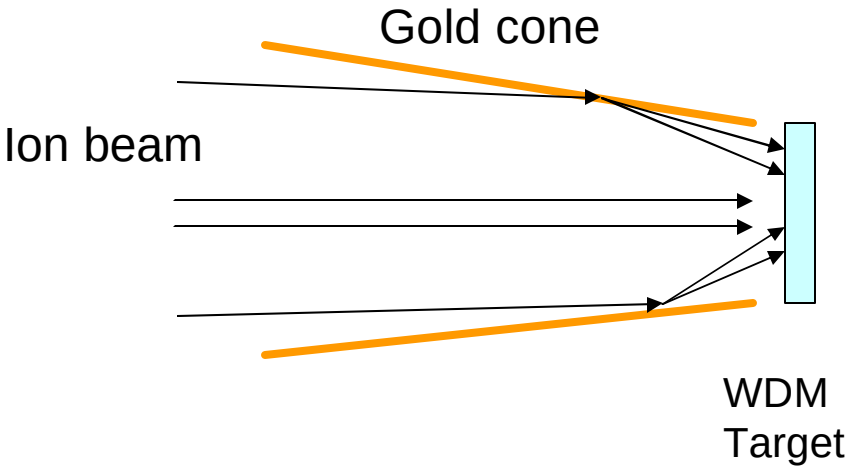
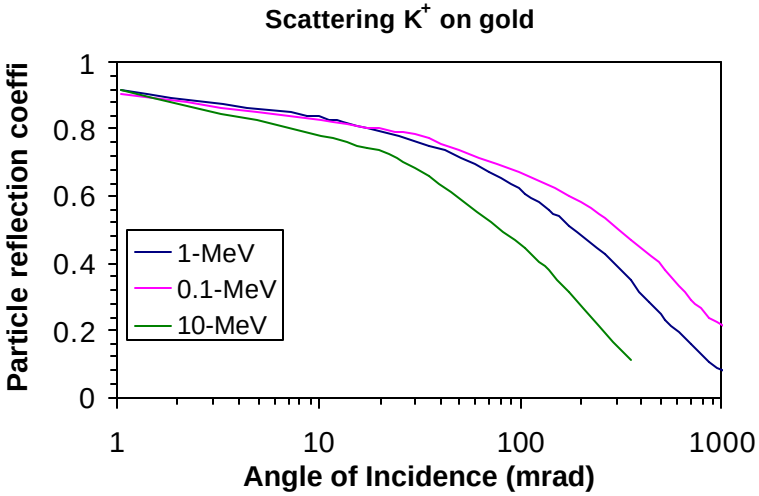


WARM DENSE MATTER TARGET CHAMBER



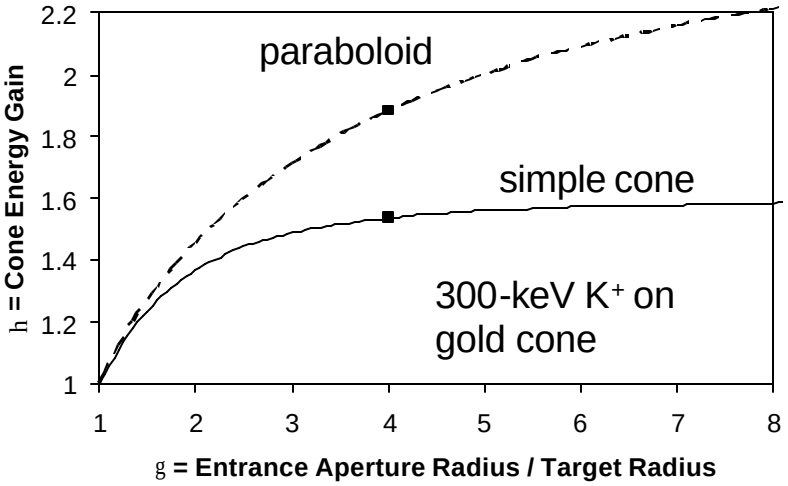
Funnel (cone) to concentrate ion beam energy density on target has several advantages.





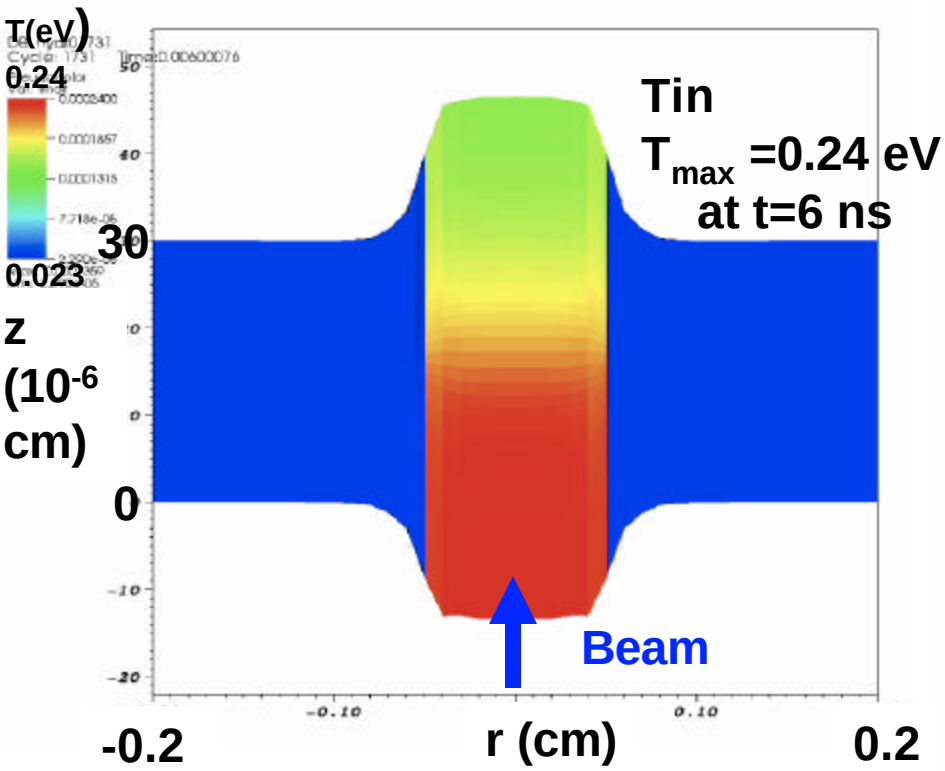
- **Cone acts as grazing incidence mirror. Enhanced ion intensity using cone has been demonstrated.**
- **Space charge neutralization of beam electric field by presence of walls, electron production may improve final focus on target.**
- **Cone shields target from unwanted heating by edge of beam.**

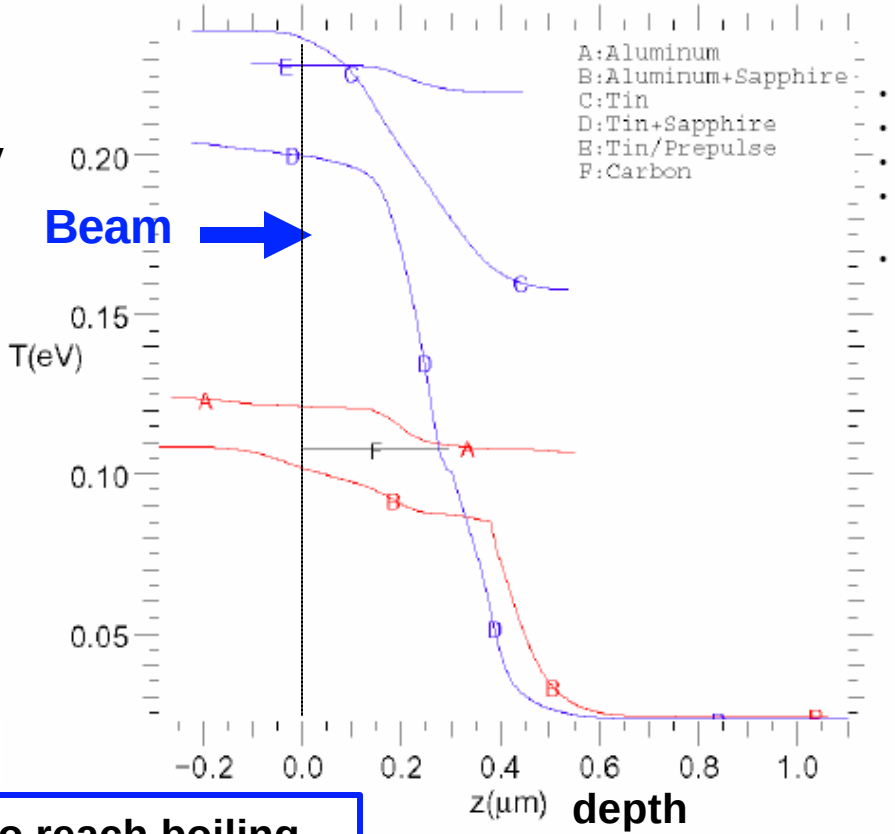
TRIM calculations for a single reflection



HYDRA simulations of NDCX-I planar targets predict temperatures of a few tenths of an eV.

Simulation assumptions: Ion energy: 350 keV Energy fluence: 0.1 J/cm^2 Spot radius: 0.5 mm Pulse duration: 2ns FWHM Total energy deposited: 0.8 mJ Peak current: 1 A (40 times compression) Total charge: 2.3 nC





HYDRA simulations by Enrique Henestroza

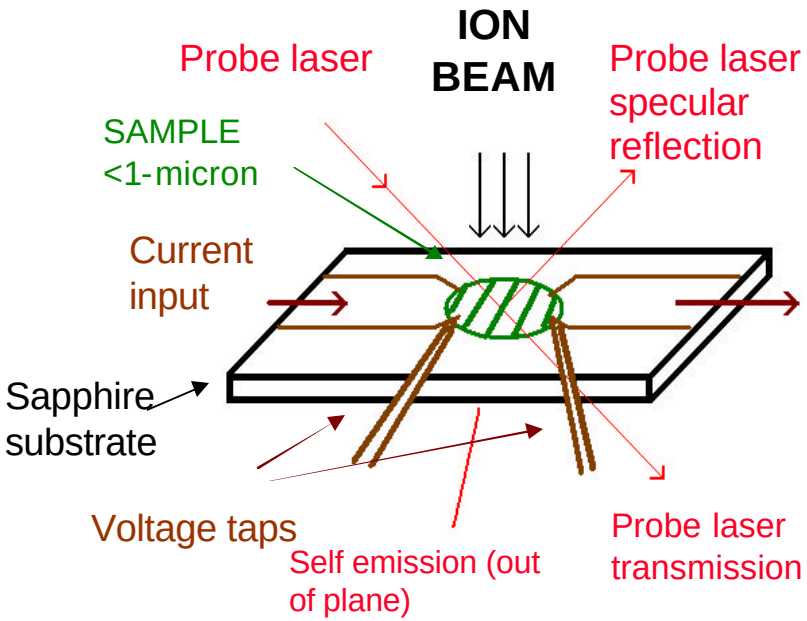
Energy required to reach boiling point (J/cm^2): 0.12 (Au); 0.25 (Al)

Initial experiments test diagnostics for WDM targets.

Initial diagnostics will include

- Optical emission, especially high speed optical pyrometer
- High speed I-CCD cameras
- Streak camera
- Optical spectrometer
- VISAR probe

Future: laser, conductivity probes etc.

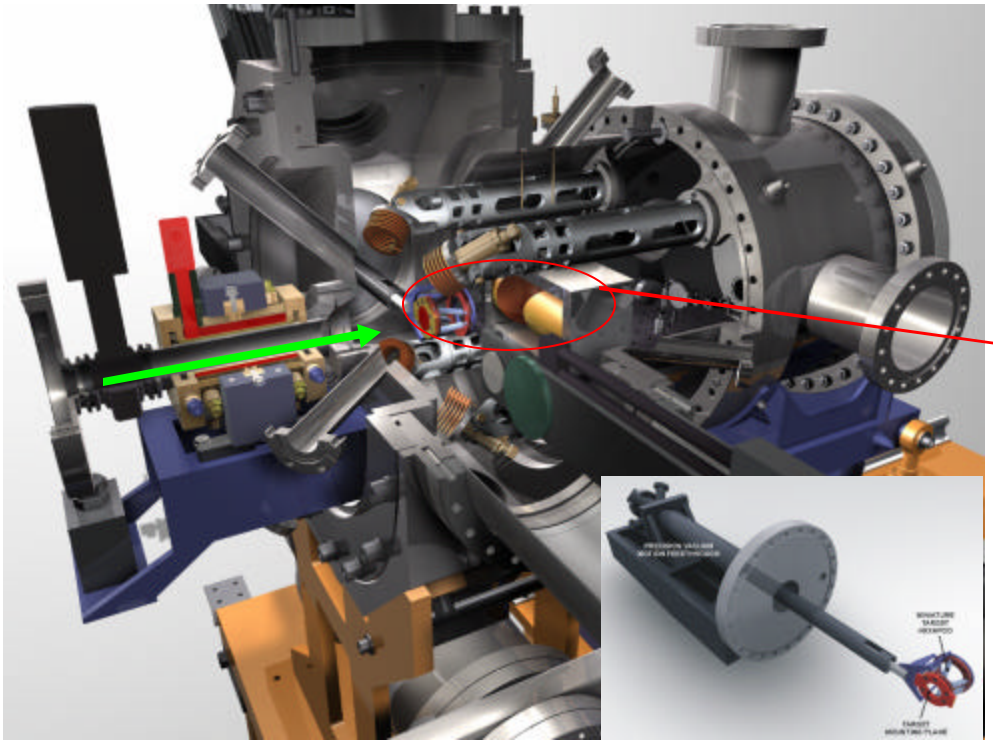


Initial set of targets

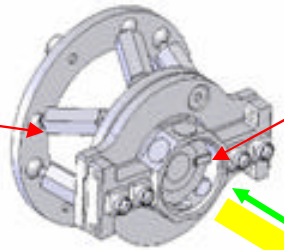
- Deposited on sapphire substrate
  - Al: 350 nm
  - Au: 150 nm
  - W: 150 nm
- Free-standing foils
  - 350-nm Al
  - 150 nm Au
  - 120 nm Pt
  - 400 nm Si

Optical diagnostics of target

Target chamber:



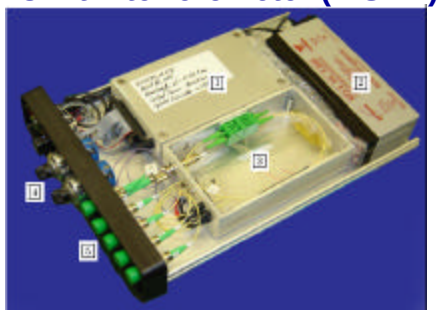
Probing of target:



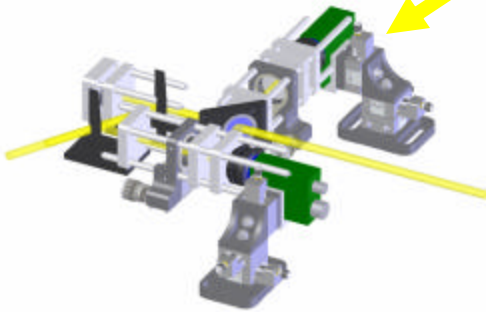
Heated sample

Fiber bundle

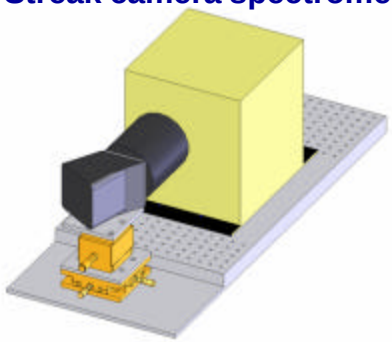
Doppler-shift interferometer (VISAR):



Pyrometer:

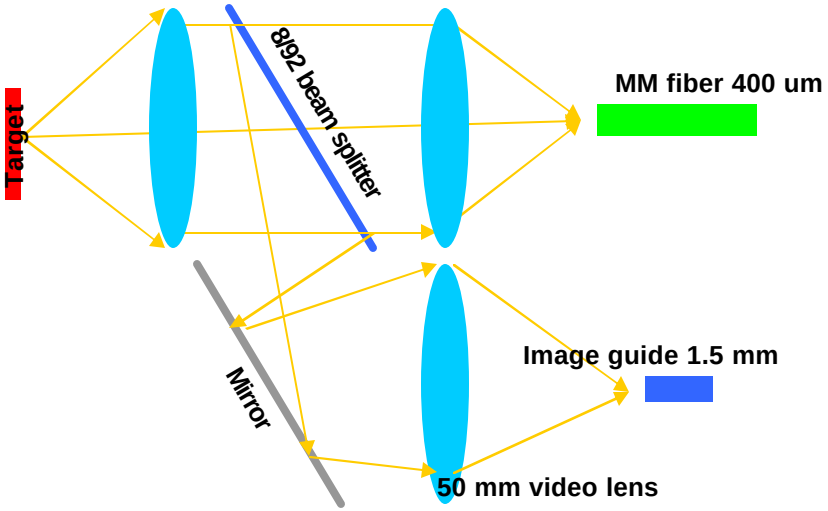


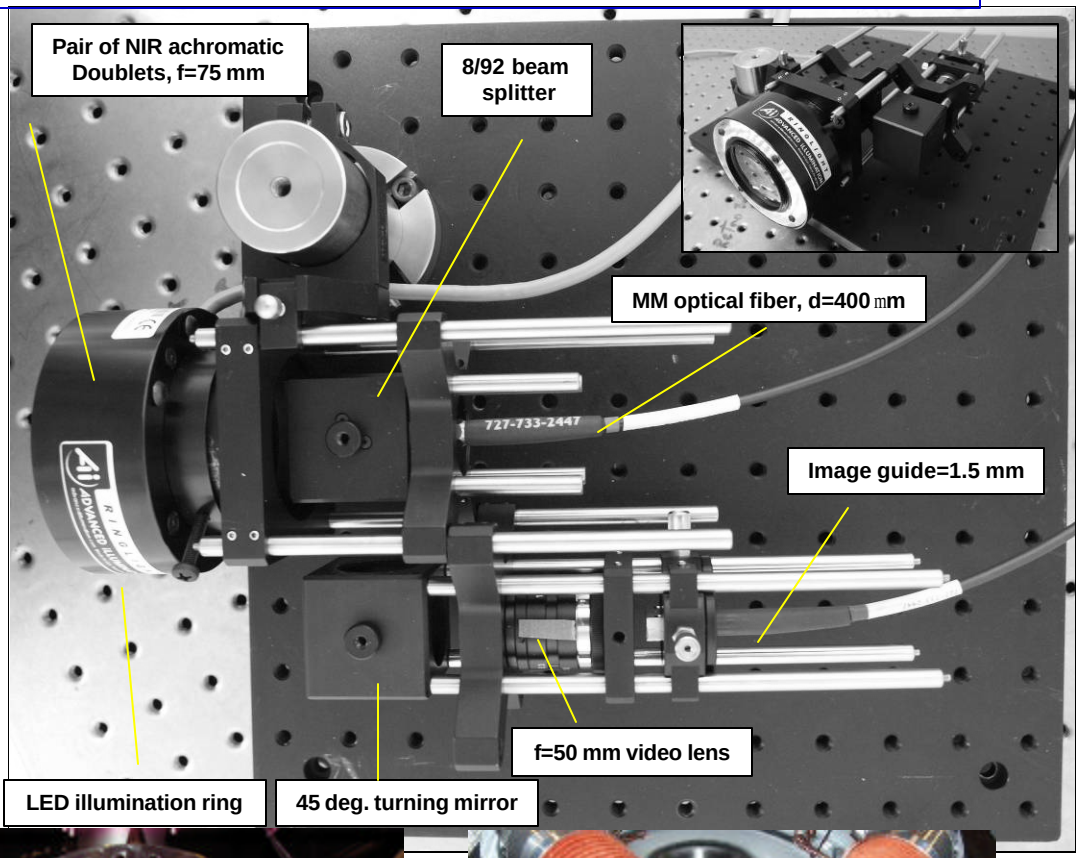
Streak camera spectrometer

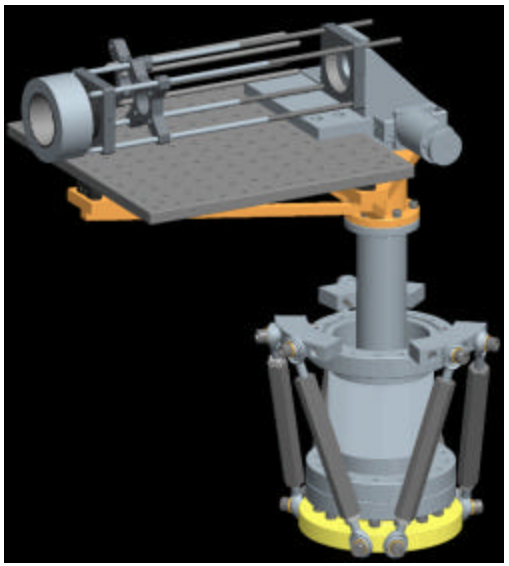


Light collection/probing system

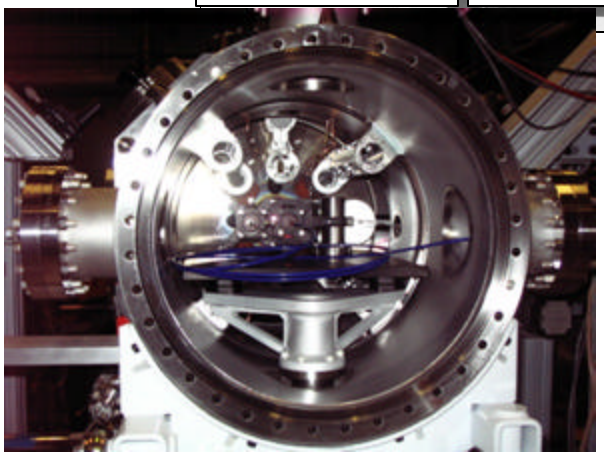
2 x NIR achromatic doublets, f=75, d=50.8

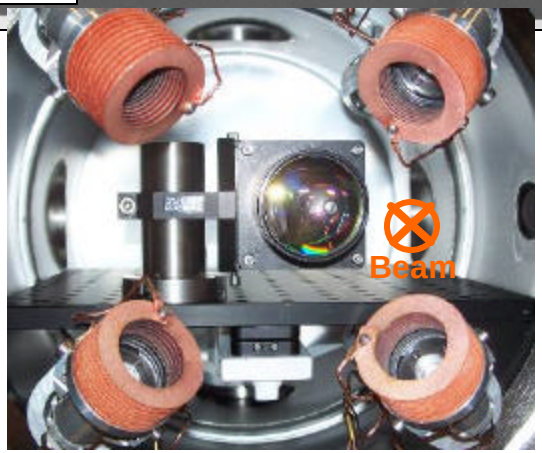




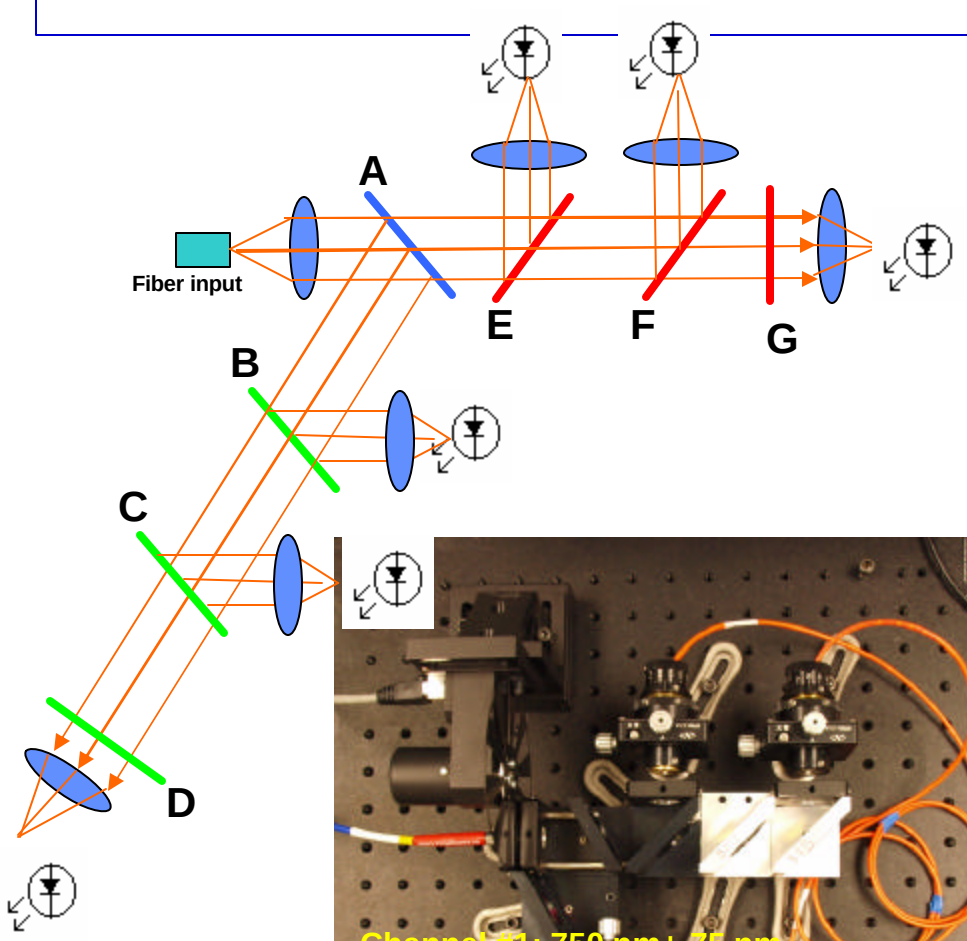


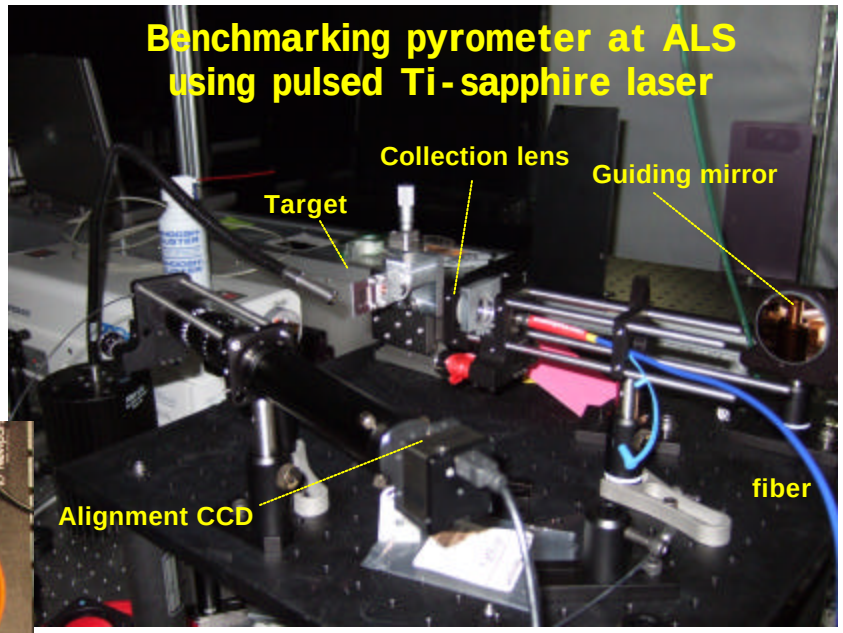
P Ni

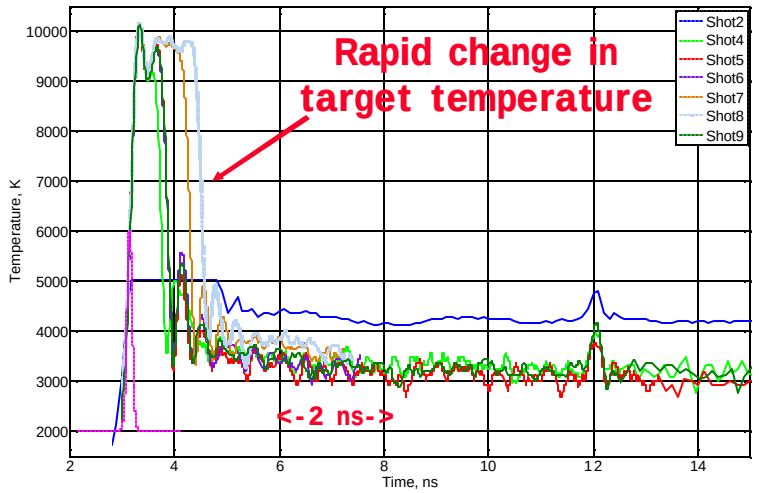




Ultra-fast optical pyrometer for experiments at NDCX







P Ni

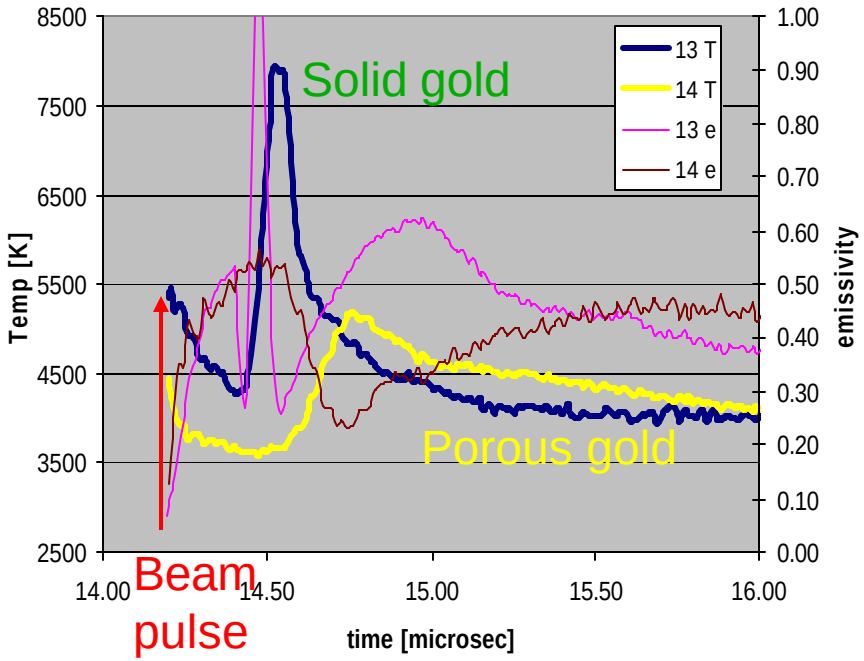
Near-term NDCX-1 experiments plan to explore phase transitions in heated targets.

- Characterize NDCX beam using beam and target diagnostics – prepulse, compressed pulse, pulse-to-pulse reproducibility
- Test scintillator, gas-based beam spot diagnostics
- Test gold cone
- Use pre-heat to reach boiling point, then use compressed pulse to explore liquid-gas phase transition (e.g. droplet, bubbles)
- High-electron-affinity targets (gold, iodine)
- Porous targets (e.g. gold black) to lengthen expansion time of target foils
- Diagnostic commissioning and diagnostic development: improved pyrometer sensitivity, optical polarimeter
- Silicon target: relevant to NIF damage control

Porous target slows expansion compared to response of solid target to ion beam pulse.

- Beam range increases in porous target, slowing down hydro expansion time
- Very low density porous targets, such as gold black, can increase expansion time by factor ~100
- Target expansion time can be >> compressed pulse length ~2 ns.
- Modeling of porous target response is underway

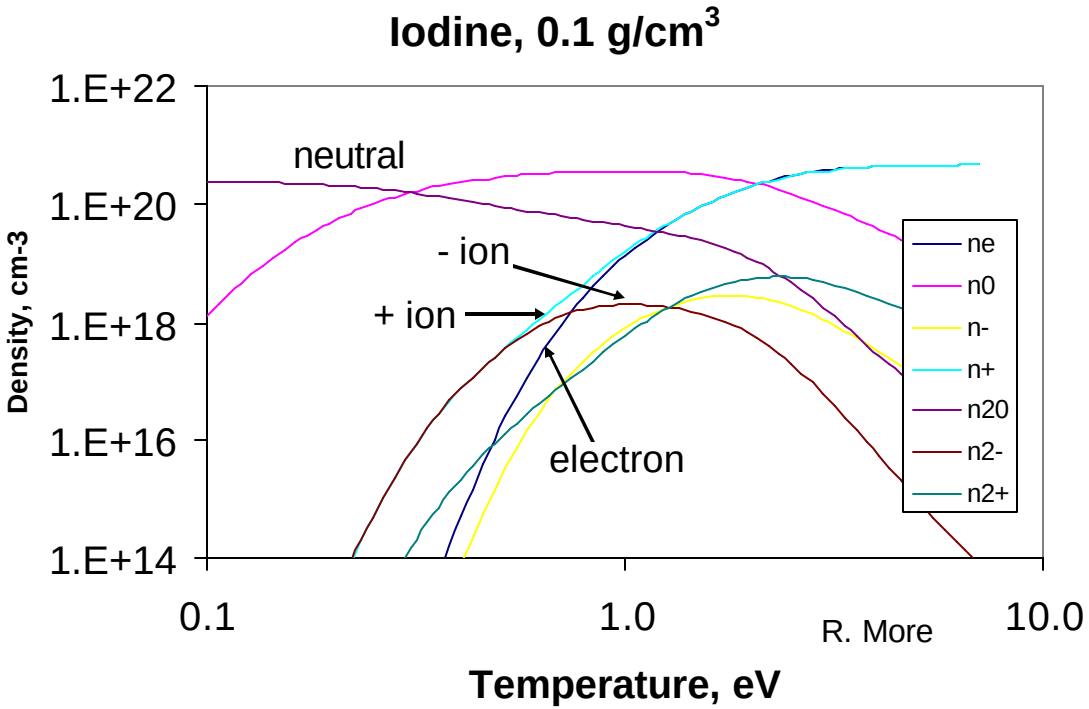
Pyrometer data comparing response of porous and solid target at GSI



Experiment in high electron affinity targets

Electron affinity:

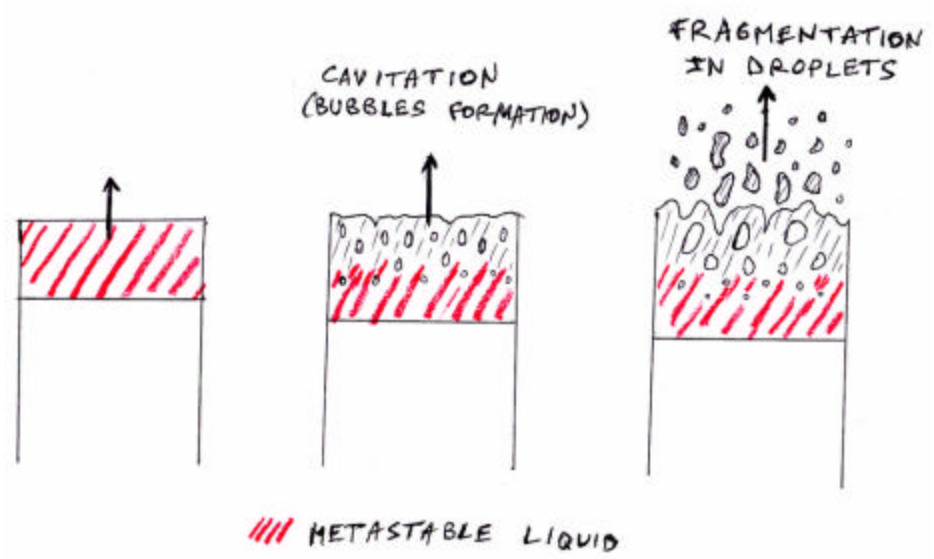
Au	**2.3 eV**
I	**3.1**
Br	**3.4**



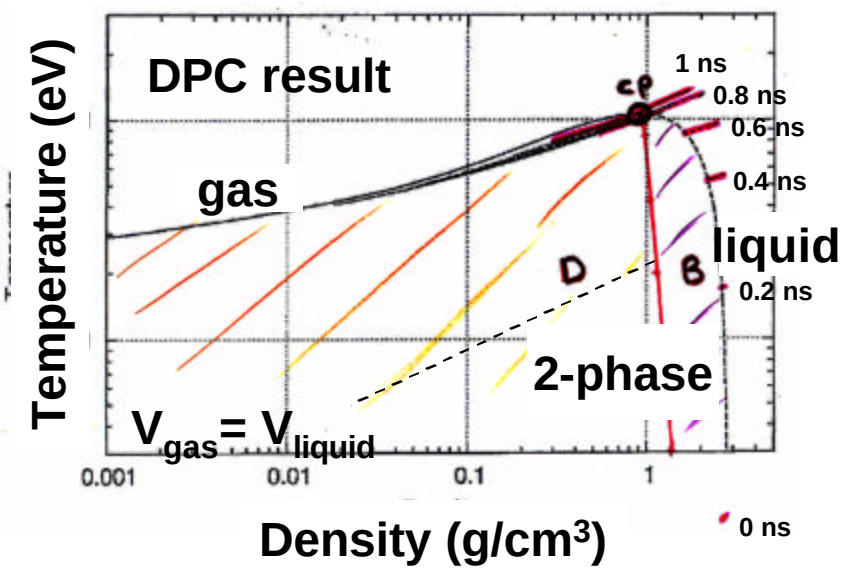
- **Unusual material – dominated by +/- ions**
- **narrow temperature range; e.g. 0.4 to 0.7 eV for iodine at 0.1 g/cc.**
- **radiation from charge exchange**
- **expect conduction by charge transfer**
- **Other: optical behavior, metal-insulator transition**

Formation of droplets during expansion of target in liquid – vapor two-phase region.

Target is first entirely liquid then enters two phase regime.



Example of evolution of target in r and T

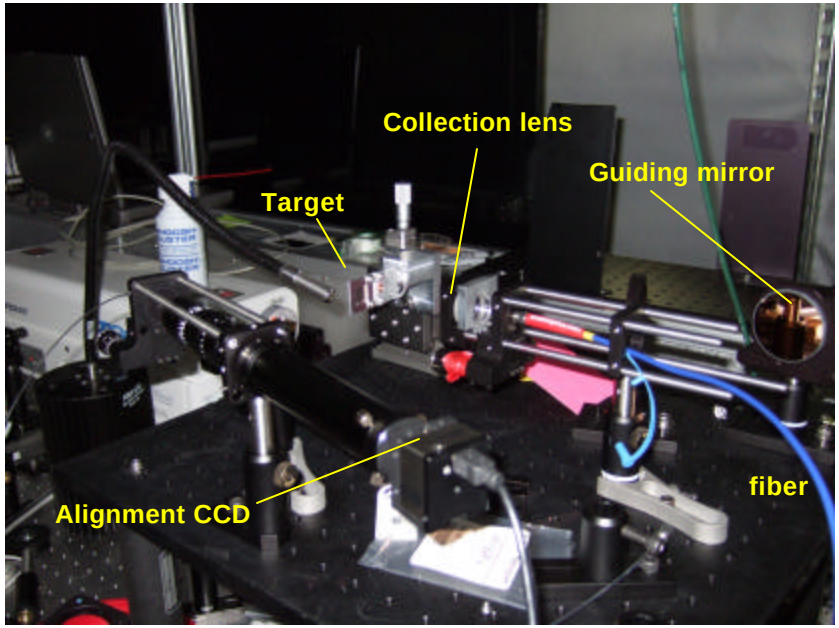


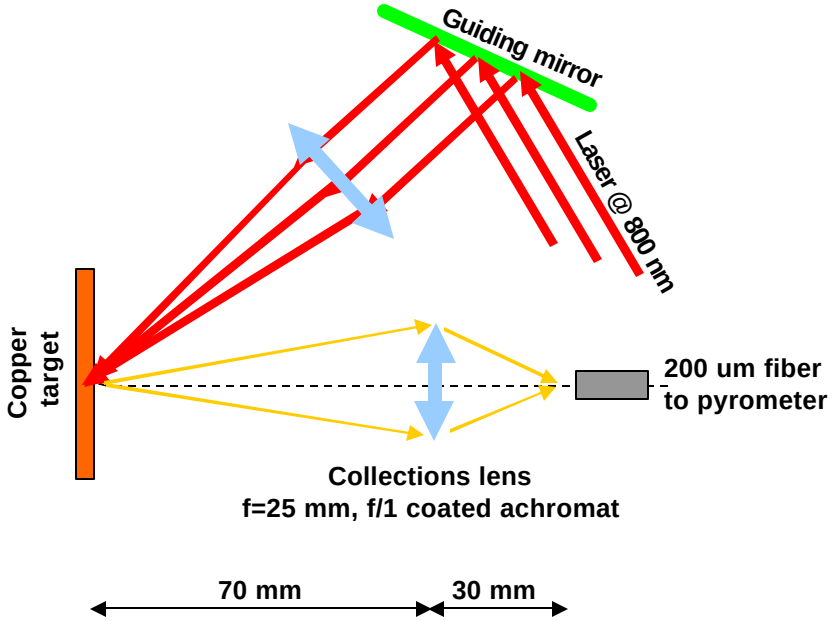
(J. Barnard, et al.)

Summary

- Ion beams provide a new tool to generate homogeneous WDM.
- Existing pulsed accelerators and pulse compression technique developed in HIFS-VNL to be used in the experiments.
- We have installed a new target chamber; developed and tested initial target diagnostics.
- Initial experiments will take advantage of beam pre-pulse to pre-heat foils; goal is to study liquid-gas phase transition region.
- Future experiments will explore e.g. high electron-affinity targets, porous targets.
- Higher temperatures, longer range expected in NDCX-II.

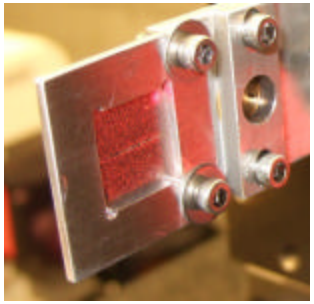
Benchmarking fast pyrometer diagnostic at ALS

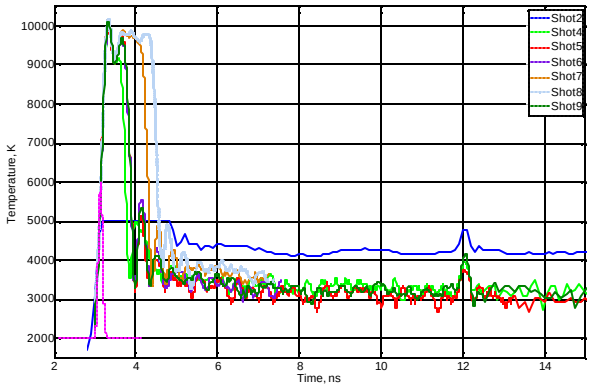


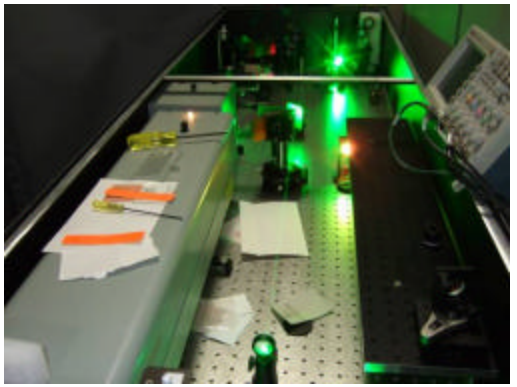


Amplified Ti-Sapphire laser @ 800 nm, pulse duration ~ 100 fs, energy 5-10 mJ, spot size 400 um

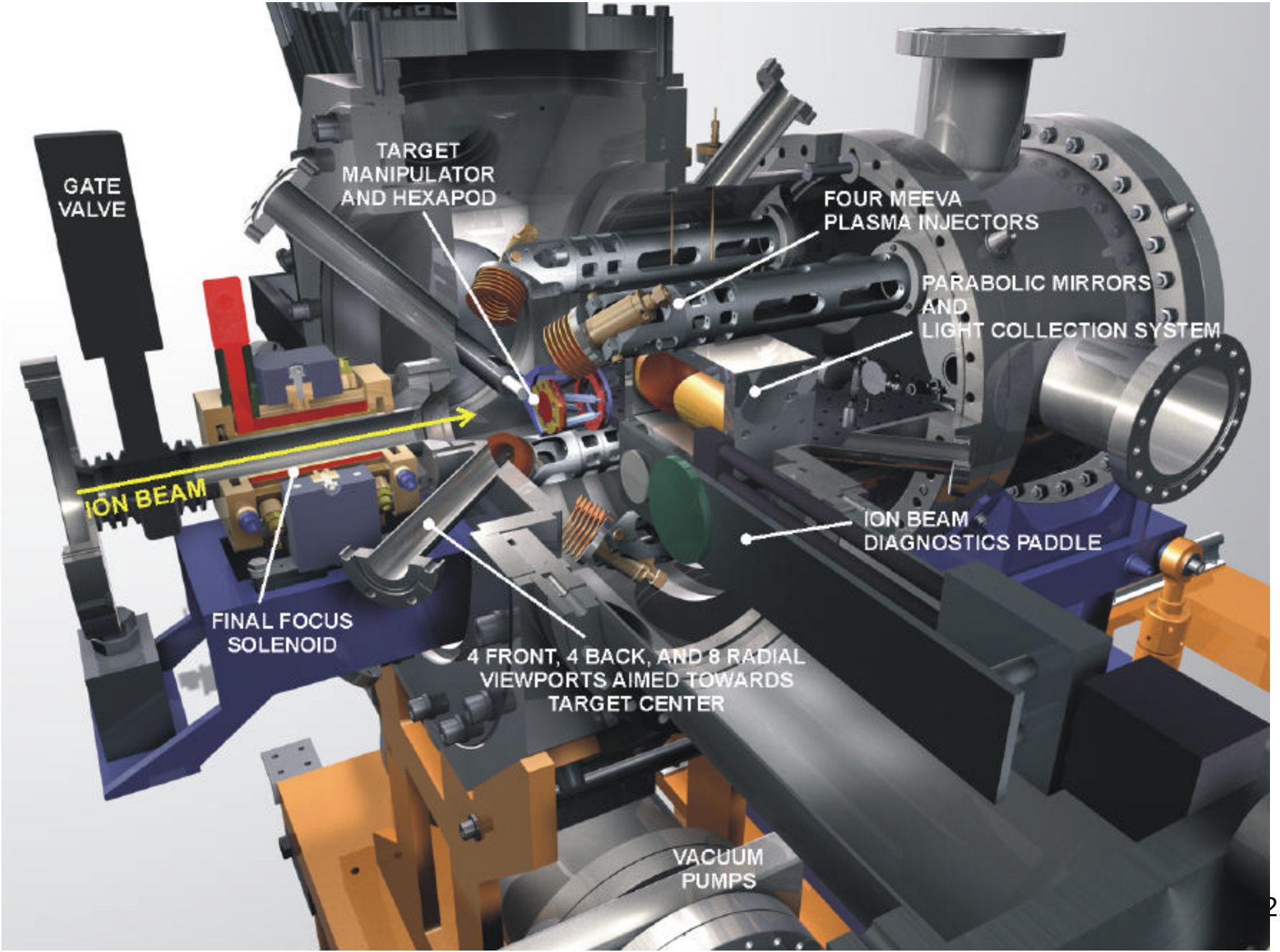
Copper target: 120 nm thick + 5 nm of protective carbon on both sides







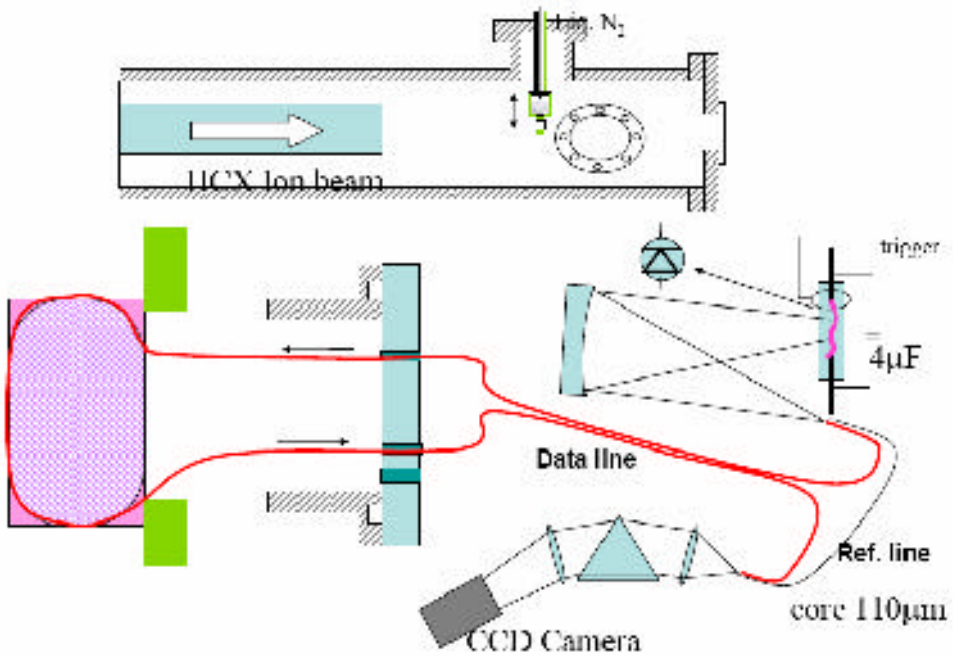
WARM DENSE MATTER TARGET CHAMBER

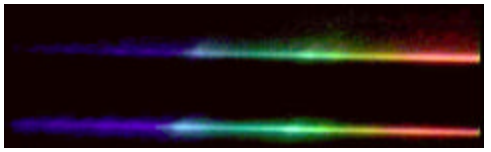


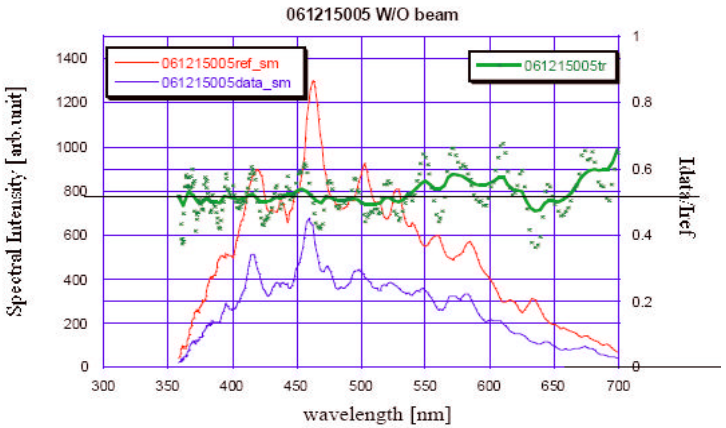
We have begun a series of experiments in warm dense matter.

- Porous target experiment at GSI to compare response of solid/porous targets:
  - Performed Dec. 2006; Analysis underway
- First beam-driven WDM target experiments at LBNL for beam and diagnostic commissioning: 2008
  - T > 0.15 eV, NDCX-1
- Low density porous target studies (e.g. gold black on NDCX-1)
- High electron affinity WDM targets
  - T > 0.4 eV, NDCX-1/NDCX-2
- Two-phase liquid vapor WDM targets: fragmentation, droplet formation
  - T ~ 0.5 – 1 eV, NDCX-1/NDCX-2
- Other EOS studies; critical point
  - T ~ 1 eV, NDCX-2
- Beam - shock-wave coupling in cryogenic targets (Ne, H)
  - NDCX-2
- Other:
  - Micro-implosions driven by ion beam
  - Thin target dE/dx, beam scattering, charge state

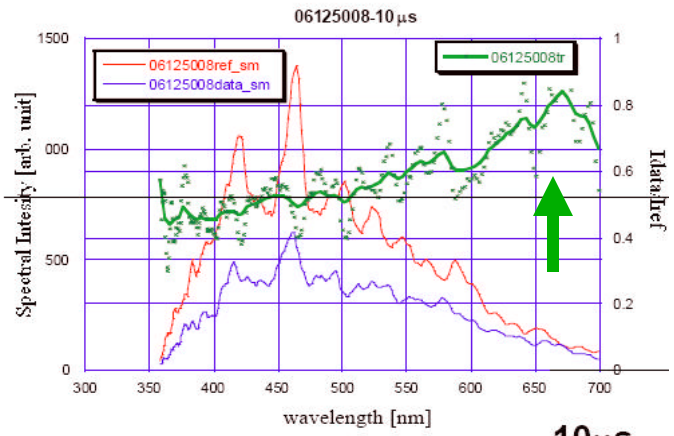
Transient optical transmission experiments in quartz fiber performed on HCX (1 MeV K^+ ion beam).







No beam



10μs

Optical transmission experiment: look for difference in fiber transmission with and without beam.

Initial experiment shows possible weak effect at 10 μs, long wavelengths ➔